Advances in Geothermal Resource Exploration Circa 2007

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ABSTRACT

At the outset of the 21st century, the geothermal community at-large is essentially attempting to use available exploration tools and techniques to find needles (geothermal occurrences) in very large haystacks (expanses of unexplored territory). Historically the industry has relied on the presence of surface manifestations of subsurface heat, such as hot springs, fumaroles, or geysers as a first-order exploration tool. Regrettably, even when such surface manifestations are investigated more closely, there is no proven technique or techniques that can be used with a high degree of certainty that will indicate the presence of geothermal resources before drilling. Advances in computer technology have propelled geothermal exploration forward, but can only go so far. New exploration concepts are needed, as are new tools, to insure that the industry has a chance of locating and developing the most geothermal resources possible at reasonable costs.

Introduction

As of 2007, it is estimated that less than 10% of geothermal resources in the United States have already been brought to market. This has resulted in slightly more than 3,000 MW of on-line power generation capability in four western states with another 1,000 MW in various stages of development. By 2010, the U.S. Department of Energy estimates that there will be more than 5,000 MW of geothermally-generated electricity available in at least six states west of the Mississippi River. Finding the additional 35,000 MW of geothermal resource that is purportedly available will require a substantial investment on the part of the rather small industry, but there are encouraging signs for success.

One thing is clear, the geothermal industry itself does not have the capability to develop new exploration techniques on its own. This is primarily due to there not being sufficient cash flow to permit the type of risk-taking required to test new techniques or strategies to find geothermal occurrences. It is also due, in part, to the fact that the industry cannot justify funding to financiers for those types of endeavors. For the most part, then, it is the academic community that has the opportunity to formulate and test new and innovative exploration concepts and tools because of the availability of research grant-type funding. Once the techniques and/or strategies are proven, industry can convince financiers that the necessary investment capital they are going to have to put into the effort is more likely to result in new resources being brought to market.

At the present time, the geothermal industry, academia, and the U.S. Department of Energy Geothermal Program Office (DOE) are casting about for the exploration equivalent of the oil & gas industry's reflection seismic exploration technology. In the oil and gas business all exploration techniques are subordinate to reflection seismic exploration technology because those techniques have been shown to be very reliable, versatile, and cost-effective in finding and characterizing hydrocarbon resources in place – before the drill bit is put in the ground, which is the expensive step. In the meantime, for the geothermal industry, there are some promising new tools and techniques that can greatly facilitate locating and evaluating geothermal resources in many geologic settings.

Figure 1, overleaf, illustrates these new tools and techniques couched within an overall exploration scheme that involves three steps: regional reconnaissance, prospect identification, and project appraisal. These steps heavily emphasize data synthesis, remote sensing, and data manipulation. The subject disciplines have not changed much over the years, e.g., geology, geochemistry, structure, and so on, but the real payoff comes in the synthesis phase. The exploration process characteristically involves large amounts of data that demand fast and efficient tools for manipulation and analysis.

Where Does the Geothermal Industry Stand Regarding Exploration?

There are encouraging signs that new, faster, more inclusive, and more reliable exploration tools are becoming available to help in the quest for additional geothermal resources. These come in a wide variety of disciplines, many of which are non-

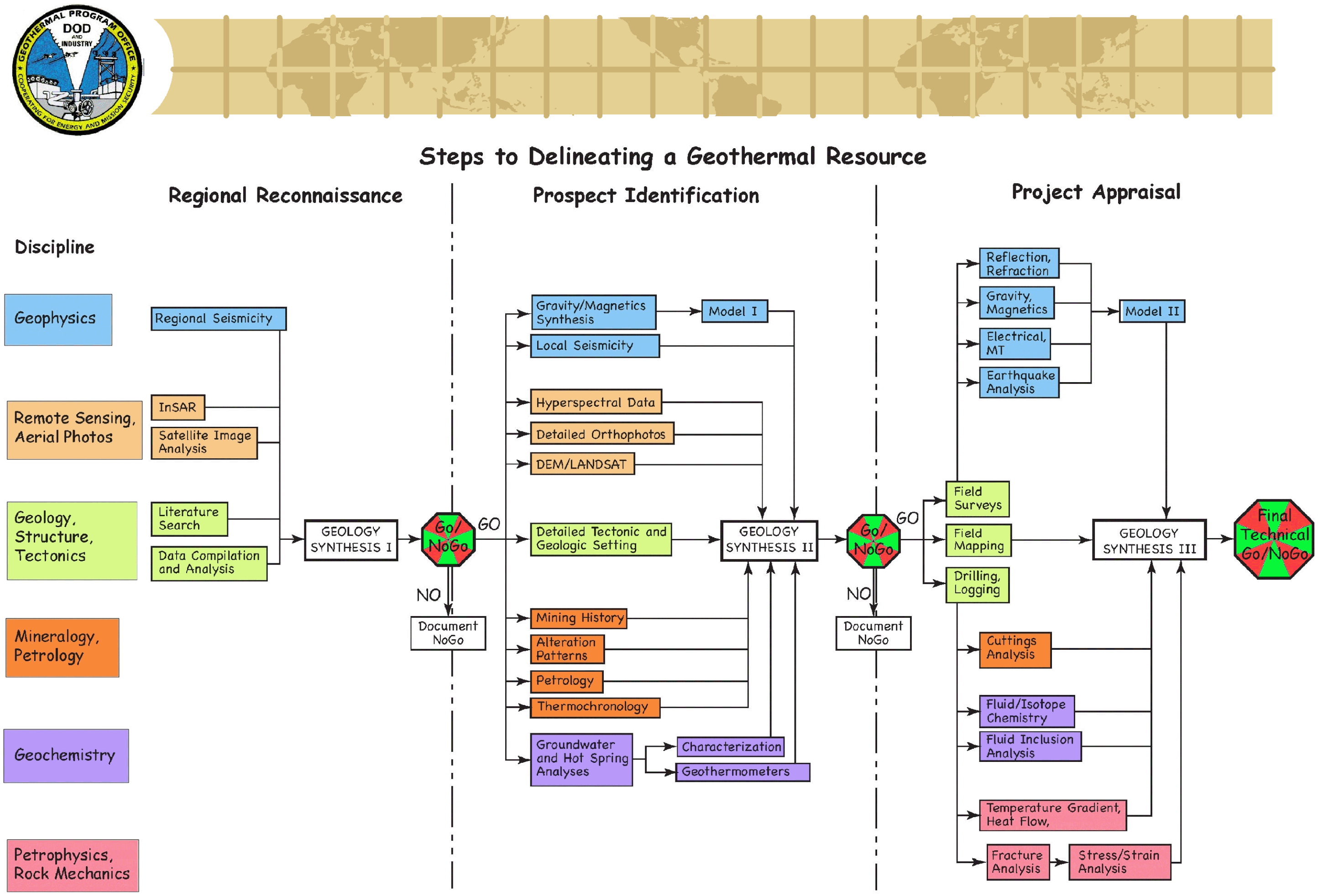

Figure 1. An exploration scheme for locating and evaluating geothermal resources. Each phase is highlighted by a synthesis of information followed by a go/no-go decision that is based on likelihood of success in finding geothermal resources and the associated economics of the exploration effort.

traditional. In fact, advances in the traditional scientific and technical disciplines are seriously lagging behind industry need. The most significant recent advances in exploration have been realized in:

- digital field mapping;
- geodetic measurement and analysis;
- remote sensing;
- thermochronometry; and,
- technical and scientific database creation and manipulation.

The common denominator in all of these advances is their roots in the explosion in computer technology. It is unquestionable that the dramatic increases in speed, storage capability, miniaturization, and reliability of microcomputers has resulted in the proliferation of computer-based tools and techniques that enable scientists and engineers to perform near-real-time analyses, in the field, using greater volumes of disparate data.

Digital Field Mapping

Pioneered in the mid- to late-1990's, digital field mapping has become a staple of university curricula in geology. One of the leaders in the field, the University of Kansas, has been conducting digital mapping as part of their field methods course since 1997 (Walker and Black, 2000). They have pioneered the integration of digital geologic data acquired with in-the-field precision geodetic data from satellites (Walker et al., 1996). These are all overlain onto digital elevation models and other available historical geological and geophysical data.

The tools for digital field geologic mapping are readily available and include relatively simple hand-held GPS units and pocket computers (Coolbaugh et al., 2004), as well as top-of-the-line, field-hardened, ruggedized laptop computers that have been mainly developed for military use. Battery life remains an annoyance, but careful management of actual run time can obviate premature failure. These machines are so durable that they can withstand a full-grown adult falling on them and still operate. The result is availability of geologic maps at the end of a field day that are in near-finished format. Of course, the usefulness of the map still depends on the skill of the geologist doing the mapping, but the tools facilitate the process.

Geodetic Measurement and Analysis

Hand-in-glove with digital field mapping is the availability of space-based geodetic data from the Global Positioning System

(GPS) satellite network. This network provides a spatial reference frame with unparalleled accuracy. Developed by the military in the 1960's and 1970's in response to evolving needs for accurate and precise geodetic data for input to rocket trajectory calculations, GPS has matured into a network of 24 geostationary satellites orbiting 3,353 km (11,000 miles) above the earth's surface, each equipped with precision atomic clocks to keep accurate time. GPS has developed into a worldwide precision location system capable of providing real-time data in the field via hand-held receivers. Ten years ago, hand-held GPS units generally provided data with position errors of ±10 to 15 meters, but with changes in coding techniques and rules regarding selective availability (degradation of the location grid by the military), newer units can produce accuracies of less than 5 meters in the field, and a few centimeters after locations are differentially corrected in the laboratory. For comparison, a sharp pencil line on a 7.5' topographic map is equal to about 7 meters in width.

Data with this type of accuracy greatly improves reliability of geologic mapping, location of geophysical and geochemical sample sites, and subsequent integrated analysis for geologic structure and tectonics. These, in turn, greatly increase the probability of correctly interpreting available exploration data and actually finding geothermal resources in a timely and cost-effective way.

One of the most dramatic applications of GPS data has been in crustal motion studies. Measurement of horizontal secular motion of the earth's crust has been on-going since the early 1980's (Savage, 1983; Christodoulidis et al., 1985; Herring et al., 1986), but data from space-based systems only became available in the 1990's (Robbins et al., 1993). Improved GPS software analysis programs developed by Dong and Bock (1989), Beutler et al. (1987), and Blewitt (1989) have actualized the data applications so that sub-millimeter accuracies can be achieved in the horizontal plane.

Crustal motion studies are the basis for determining areas of high-strain rates in the earth's crust which have been directly correlated with occurrences of geothermal resources (Blewitt et al., 2002). Garside and Schilling (1979) were among the early investigators who associated geothermal occurrences with active faults in the U.S. Basin and Range, and Sabin et al. (2004) recognized its importance in geothermal occurrence models. This concept combined with the known crustal extension, and attendant crustal thinning, in the Basin and Range forms the basis for interest in areas having high values for horizontal plane strain rates. Recent work by Blewitt (2005) has demonstrated the feasibility of fielding large numbers of continuously-recording GPS receivers thus providing more dense spatial coverage in areas of active tectonic regimes.

Remote Sensing

When one thinks about remote sensing in today's exploration environment, one takes for granted the availability of powerful tools that can cover large expanses of the earth's surface in a very short period of time and produce images of hundreds of square miles with dramatic clarity. The road leading to where we are today in the realm of remote sensing has, however, been anything but straight and without obstacles.

After the Russians launched Sputnik in 1956, and spurred by the military concerns brought about by that event, scientists in the United States took seriously the possibilities of using satellites for imaging the surface of the earth. Four years after the landmark launch of Sputnik, the U.S. launched their first earth imaging satellite called Television and Infrared Observation Satellite (TIROS). While crude by today's standards, images from that satellite provided useful views of the earth's solid surface and encouraged additional research into improving resolution and coverage using space-based technology. After a series of satellites in the 1960's and 1970's (Geostationary Operational Satellite (GOES), Nimbus, Seasat), the U.S. launched their first dedicated land imaging satellite, Landsat, that provided high-resolution multi-wavelength images of the earth via a device known as a Thematic Mapper. This was followed six years later by a successful launch by the French of the Satellite Pour l'Observation de al Terra (SPOT) satellite that was the first in a series of satellites for the commercial production of images of the Earth.

There are a number of platforms in operation today that can provide high quality images of the surface of the earth in a variety of bandwidths, e.g., SPOT, EOSAT, European Space Agency ERS, Terra, and others). Images from these platforms are the basis for important analytical technologies such as ASTER and INSAR, both of which have proven of great value in exploration and monitoring of promising geothermal areas.

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) produces high-resolution (15 to 90 square meters per pixel) images of the Earth in 14 different wavelengths of the electromagnetic spectrum, ranging from visible to thermal infrared light. Scientists use ASTER data to create detailed maps of land surface temperature, emissivity, reflectance, and elevation. The ASTER system consists of three telescopes (VNIR, SWIR, and TIR) that can be pointed to provide data in bands that are orthogonal to the direction of satellite travel. Given its high resolution and its ability to change viewing angles, ASTER also is capable of producing stereoscopic images and detailed digital elevation models. From a geothermal point of view, the technology is being tested in known geothermal fields, such as Coso in east-central California, with special emphasis on the thermal infrared bandwidth to detect variations in surface heat (Eneva et al., 2007). The airborne equivalent of ASTER is the MODIS/ASTER, or MASTER, developed in 1999 by NASA Ames Research Center. This device has 50 spectral bands covering everything from short-wavelength infrared to long-wavelength infrared with resolution as high as 4 meters. This technology has been successfully used in mineral mapping studies of active and inactive hot springs sinter deposits (Kruse, 2002), and clay mineral distribution in areas of epithermal gold deposits (Kruse and Hauff, 1991).

Airborne-based hyperspectral imaging has been in use since the early 1980's (Goetz et al., 1985), but has only become widely applied to geothermal exploration since 2000. The technique is based on reflectance or emission of rocks and minerals in the bandwidth ranging from 450nm to 2500nm wavelength range. Depending on the sensor, data are recorded over more than 100 wavelength channels over a 512 pixel swath (Martini et al., 2003). Although the technology had been used in mining exploration since the late 1980's, Martini (2002) did the seminal work on geothermal applications using the Long Valley (Casa Diablo geothermal area) as a test bed. This was followed by several studies that utilized the technology to examine reflective differences in plants (Pickles et al., 2001; Pickles et al., 2003), hydrothermal alteration (Kennedy-Bowdoin et al., 2003) and mineral identification using remote sensing in direct support of geothermal exploration (Martini, et al., 2003; Martini et al., 2004; Kratt et al., 2006).

InSAR is an acronym for Interferometric Synthetic Aperture Radar. This is a space-based technology capable of producing images that have sub-centimeter resolution in the vertical dimension with pixels <10 meters on a side. It has been particularly helpful in pinpointing areas of extreme crustal movement, thus, areas where high strain rates exist. Although InSAR has been used in the past for determining subsidence and uplift related to geothermal production (Fialko and Simons, 2000; Wicks et al., 2001), recent efforts by Foxall (2006) show promise for the tool in identification of regional and sub-regional exploration targets.

LIght Detection And Ranging (LIDAR) is one of the hottest new technologies available to the geothermal exploration world. It operates similarly to RADAR but uses transmitted light from an active source that is bounced off passive bodies and recorded in an airborne platform. Airborne LIDAR systems collect simultaneous horizontal and vertical data at specified time intervals and can achieve accuracies of ±15cm in both the horizontal and vertical planes. This permits the imaging of very small irregularities in the surface of the earth that generally go undetected by conventional field mapping. In particular, this technology can be extremely helpful in identifying fault scarps that are present in unconsolidated sediments that are indicative of Holocene tectonic activity – another key element associated with geothermal occurrences. MacNight et al. (2005) provide an example of using this technology to map young faults in unconsolidated sediments at the Rye Patch and Humboldt House geothermal systems in western Nevada.

Thermochronology

Thermochronology involves determination of temperature-time sequences for particular minerals commonly found in plutonic and volcanic rocks (Farley and Stockli, 2002). Examples are zircon, apatite, titanite, monazite, rutile, magnetite, and xenotime. The technology is based on radioactive decay of naturally-occurring isotopes of uranium and thorium that have very long half-lives. This permits accurate determination of rates of uplift and attendant depths that closure temperatures were reached.

The thing that makes this technology so successful is the continuing improvement in sensitivity thresholds of mass spectrometers and development of calibration techniques that permit reliable detection of extremely small quantities (nanograms) of the key isotopes. Ages of rocks can now be established with variances in the range of ±2 to 5 thousand years. Figure 2 shows a comparison of the state of thermochronology 10 years ago versus today. It shows that the number of minerals that can be used in this technique has tripled and that

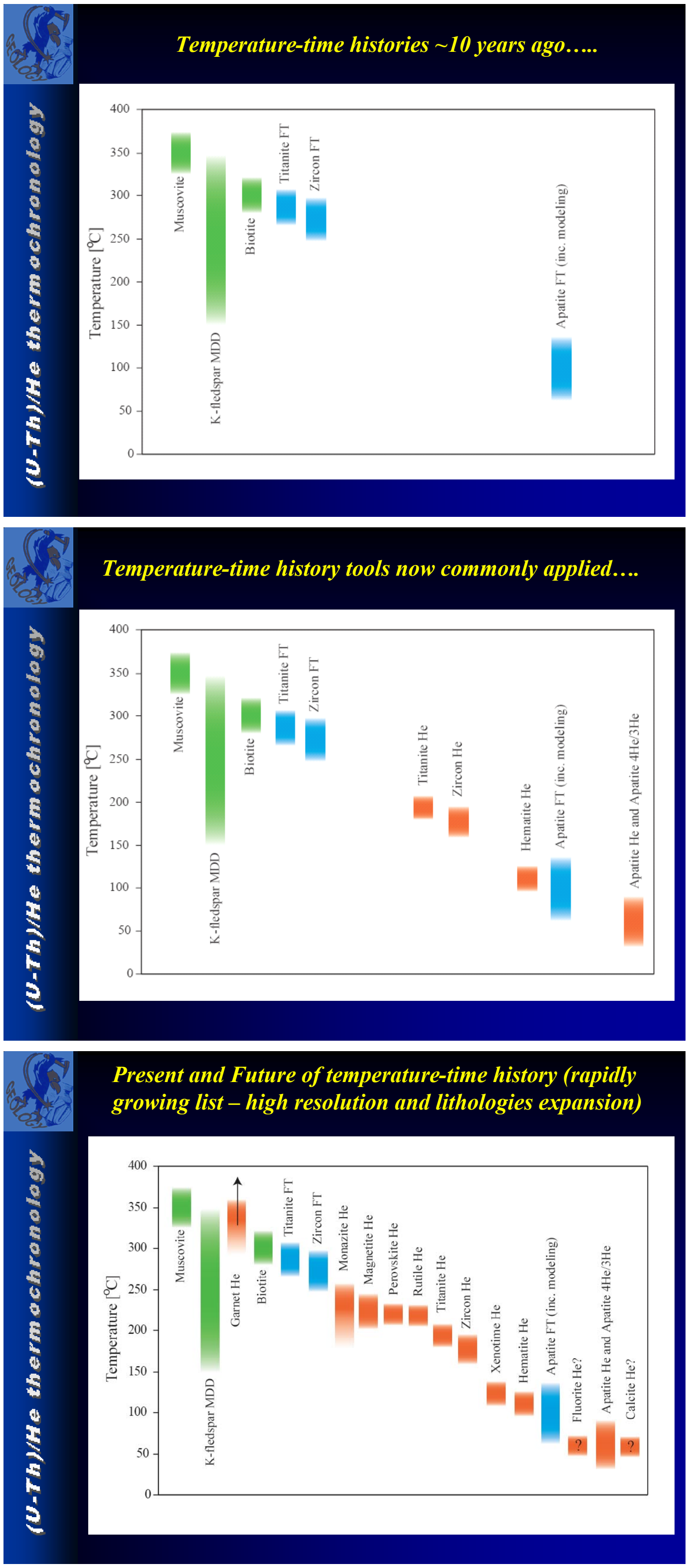

Figure 2. Diagrams show the progression of availability of various mineral thermochronometry techniques over the past 10 years. Figures are used with permission of Dr. Danny Stockli, University of Kansas, Geology Department, Lawrence, KS.

the degree of resolution on actual closure temperature has been increased by four times. It is a relatively inexpensive and quick method to get a measure of advection of mass and heat which is a powerful tool in determining the source of heat in geothermal systems, the age of those systems, and their stage of tectonic development. Two examples of successful applications of this technology are Stockli (2005) and Stockli et al. (2002) wherein the authors were able to achieve precision better than 5% with one sample and 1-2% with multiple analyses on minerals from the same sample. With these data, they were able to construct paleodepth curves for various levels in plutons that show clear and distinct inflection points indicating changes in rate of uplift and/or exhumation of crustal rocks. These types of studies are relevant to exploration inasmuch as they provide insight into mass and heat advection in the upper crust.

Technical and Scientific Database Creation and Manipulation

One of the most dramatic improvements in geothermal exploration over the past 10 years has come as a result of the advent of comprehensive, computer-based data management and analysis tools. Prominent amongst these are those based on Geographic Information Systems (GIS) technology such as ArcInfo, including ArcGIS, and its associated program ArcView. A GIS is a database that is digitally cross-referenced to spatial location. Diverse types of co-registered digital maps of geology, geophysics, and geochemistry can be brought together in a GIS database so that their interrelationships and correlations with geothermal activity can be quantitatively analyzed and assessed. A GIS provides the opportunity to use computer processing methods and spatial statistics to:

- Emphasize or enhance main features associated with geothermal systems;
- Quantitatively assess correlations between map data and geothermal systems; and,
- Combine diverse data together to produce predictive maps of geothermal potential, or, in other words, to quantitatively rank geothermal targets based on the intersection of multiple favorable geological, tectonic, geophysical, and geochemical features.

Coolbaugh et al. (2002, 2004, 2007) and Yousefi et al. (2007) provide examples of using a GIS, spatial statistics (including weights of evidence and logistic regression), and Boolean logic to produce geothermal potential maps and quantify relationships among predictive data and geothermal systems. Garcia-Estrada and Lopez-Hernandez (2003) discuss the use of a GIS to help identify drilling targets at the Los Azufres, Mexico, geothermal district.

Geothermal GIS databases are effective only if relevant data are available in digital format for computer processing. With the rapid growth in digital data bases, tied in part to internet use, more and more data are becoming readily available. These data includes DEM's, geo-referenced orthophotos, remote sensing images, and much geophysical, geological, and geochemical data. In addition, there are myriad new, expansive technical databases available in the open digital literature that can be used in conjunction with in-house data. Without generating very much new data, a company desiring to do exploration can avail themselves of rock geochemical data (e.g., www.navdat.org and www.earthchem.org), downhole temperature data (www.smu.edu/geothermal/heatflow /heatflow.htm), seismicity data (SCEC, northern California network, and Nevada Seismic network), surface geomorphic data (Google earth, Landsat images), and much more.

Success of Geothermal Exploration Depends on . . .

Geothermal exploration is situated in essentially the same position as oil and gas was in the late 1950's and early 1960's. At that time reflection seismic exploration technology methods and exploration concepts in the oil and gas industry were fairly primitive by today's standards. Drilling was largely based on surface mapping and occurrences of oil seeps. Potential fields geophysical methods provided gross approximations of subsurface structures (e.g., gravity surveys over salt domes) and single-channel acoustic reflection and refraction seismic techniques defined attitudes of buried strata, but successful wildcat drilling was still essentially confined to those areas where oil was seeping onto the surface. Revolution in the oil and gas exploration business was intimately tied to development and refinement of equipment and techniques associated with reflection seismic exploration technology surveying and data processing. Sadly, the geothermal industry in 2007 finds itself in essentially that same position.

At least two things are needed in the geothermal exploration business if there is to be any success in finding vast new quantities of resource. The first is a refined, sophisticated intellectual framework describing the occurrences of geothermal resources. In 1992, the American Association of Petroleum Geologists (AAPG) published a series of volumes entitled the "Treatise of Petroleum Geology" in commemoration of its diamond jubilee celebration of 75 years of the founding of the organization. Volume 20 of that treatise was a very incisive work called "Oil is First Found in the Mind: The Philosophy of Exploration" (Foster and Beaumont, 1992). According to the introduction to that volume, the title was a paraphrase of "a famous 1952 quotation from Wallace Pratt," eminent geologist, scholar, and businessman, who believed that "where oil is first found, in the final analysis, is in the minds of men" (Foster and Beaumont, 1992). Throughout his career with Humble Oil Company and others, he advocated the philosophy that no oil will be found if the hunter of the oil believes there is none to be found or he/she cannot visualize the setting for the hidden resource. Words like innovation, vision, and creativity are replete throughout the AAPG volume that focuses on thinking outside the box and then rigorously testing resultant hypotheses. The geothermal community should take heed and reexamine their current exploration paradigm.

The second thing that is desperately needed in the geothermal exploration business is **a** reliable, relatively inexpensive method, or combination of methods, that will serve as a set of "eyes" into the subsurface. The geothermal industry has been probing the ground in search of economic quantities of geothermal resources for more than 50 years beginning with the drilling of hot spring areas by Magma Power Company in the mid-1950s, but there remains relatively little resource that has been "discovered" and brought to market. The vast majority of economic development prior to 1970 was premised on the approach described earlier, i.e., surface hydrothermal features meant there was geothermal energy beneath. Combs (1972) states in a summary report on geothermal exploration methods, "The art of geothermal exploration is of recent origin." What is notable in Dr. Combs' report is the fact that his description of geothermal exploration techniques, applied to different localities, clearly allows for more art than science. In addition, the exploration efforts that he describes were all in places with surface hydrothermal manifestations. He discussed the strengths and weaknesses of electrical field methods, geochemical techniques, passive seismic data, results of thermal drill holes, and, last but not least, surface geologic mapping. Dr. Combs concluded that "the exploration results obtained from a single geological, geochemical, or geophysical method are not conclusive, and it is of advantage to utilize a number of complementary methods; however, in the final analysis, the drill will speak the last word" (Combs, 1972). Since 1972, there have been hundreds of millions of dollars invested by the geothermal industry and U.S. Department of Energy as well as its earlier counterparts in evaluating, developing, and testing geothermal exploration methods, but none of them approach the value to the industry that the reflection seismic exploration technology provides for the oil and gas industry.

Conclusion: ". . . and the answer is . . ."

There are two vital steps that need to be taken in order to address the exploration needs of the industry in locating and characterizing new geothermal resources before the expensive drilling stage is reached:

- First, a concerted effort must be made to develop a better array of resource occurrence models. These will provide an exploration framework for application of available technologies. Specific models that are available today need to be tested and refined, while new, innovative, "out-of-the-box" models need to be promulgated. New data synthesis tools such as GIS databases will facilitate such an effort.
- One or more new technical methods or strategies that can serve as the cornerstone of geothermal exploration need to be identified and defined. This is the equivalent of the reflection seismic technology of the oil and gas industry. This will permit the imaging of geothermal resource in the subsurface with greater accuracy and reliability. Seismology holds significant hope in this regard, but as an applied geothermal exploration science, it is greatly underutilized. Geodesy also has promise in identifying and quantifying secular strain in the crust – a parameter that has been shown to correlate positively with geothermal resource occurrences.

Dr. Combs pronouncement that, ". . . it is of advantage to utilize a number of complementary methods," (Combs, 1972) is still good and valid. The more information one has, the greater the likelihood that there will be success (i.e., steam) at the end of the drill bit. That said, however, it is also obvious that the geothermal industry will benefit from refinement of occurrence models, and developing its own equivalent to the oil and gas industry reflection seismic technology. Both of these things led to the proliferation of oil and gas fields in the U.S. in the 20th century, and they can do the same for geothermal in the 21st.

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